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Track Location Enhancements for Perspective View Displays

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EXECUTIVE SUMMARY

Three-dimensional (3-D) perspective view displays are being developed for naval air warfare consoles. Because of the inherent ambiguities of perspective projection and the lack of depth cues available in flat-screen 3-D displays, it is difficult to correctly identify the position of tracks. Our objective was to test the potential performance benefits of adding depth cues and other augmentations to 3-D displays to improve track localization. Participants viewed tracks in augmented 3-D displays or a two-dimensional (2-D) top-down display, and then reconstructed track positions on blank paper maps with track symbol pins. We found the following:

- Drop-lines and drop-shadows significantly improved the localization of aircraft over no augmentations for 3-D displays.
- Augmenting 3-D displays with drop-lines and drop-shadows improved ground-plane localization performance to the level of 2-D displays.
- Drop-lines led to the best overall localization performance for 3-D displays.
- Varying the size of track symbols with distance for 3-D displays improved localization only when there were no drop-lines or drop-shadows present.

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INTRODUCTION

Successful naval air warfare requires that decision-makers rapidly comprehend a tactical picture of three-dimensional (3-D) airspace. Conventional tactical displays show a two-dimensional (2-D) planar view of this space, populated with conventional military symbols. Information about the third dimension (i.e., aircraft altitude and attitude) is only available in drop-down text boxes when symbols are clicked on and selected (or “hooked”). Hooking is slow and error-prone (Hutchins, Morrison, and Kelly, 1996), and it can lead to inattention to the third dimension. An increasingly popular solution for simultaneously depicting all dimensions of space is a 3-D perspective view display (henceforth, simply “3-D display”). A naval example of such a display is the Area Air Defense Commander (AADC) display prototype shown in figure 1. This display is characterized by a 3-D display format and by the use of miniature realistic icons for track symbols. The naturalistic look of 3-D displays makes them appealing to users. Some have argued that their naturalism makes them inherently easier to comprehend. Dennehy, Nesbitt, and Sumey (1994) state that 3-D displays require “minimal interpretive effort.”

Although much research and development (R&D) effort is being devoted to their development, 3-D displays remain relatively untested. Recently, we measured the situation awareness of what was depicted in 3-D displays and compared it to 2-D control displays (Smallman, Schiller, and Mitchell, 1999). We also compared the identifiability of conventional 2-D track symbols with realistic 3-D icons (Smallman, St. John, Oonk, and Cowen, 2000). Here, we examine the user’s ability to localize tracks in space with 3-D displays.

Figure 1. Screenshot from an early version of the AADC 3-D display prototype (from Smallman, Schiller, and Mitchell, 1999).

BACKGROUND

Static 2-D and 3-D displays differ in their viewpoint location (see figure 2). Two-dimensional displays typically show the world from a viewpoint directly above, looking down at 90 degrees to the ground plane. Three-dimensional displays are seen from above and to the side, generally between 25 and 65 degrees to the ground plane. Both 2-D and 3-D displays suffer from ambiguities. A displayed object could be anywhere along a line of sight (LOS) between the object in the displayed world and the viewer (display user). Because the LOS runs straight down the z-axis in 2-D displays, an aircraft could possess any altitude, yet its (x,y) location is known with certainty (see figure 2, left). This complete lack of information about the third dimension was, of course, one of the main motivations for the development of 3-D displays. However, 3-D displays also suffer from LOS ambiguity, but because of the oblique viewpoint, the ambiguity about the locations of aircraft extends to all three dimensions—none of them is known with certainty (Sedgewick, 1986). This uncertainty raises questions about a user's ability to spatially localize tracks above the ground plane correctly in 3-D displays. Consistent with the notion that 3-D displays may be poor for space perception, St. John and Cowen (1999) have shown that tasks requiring precise relative position information are performed better in 2-D whereas tasks requiring general shape information are performed better in 3-D.

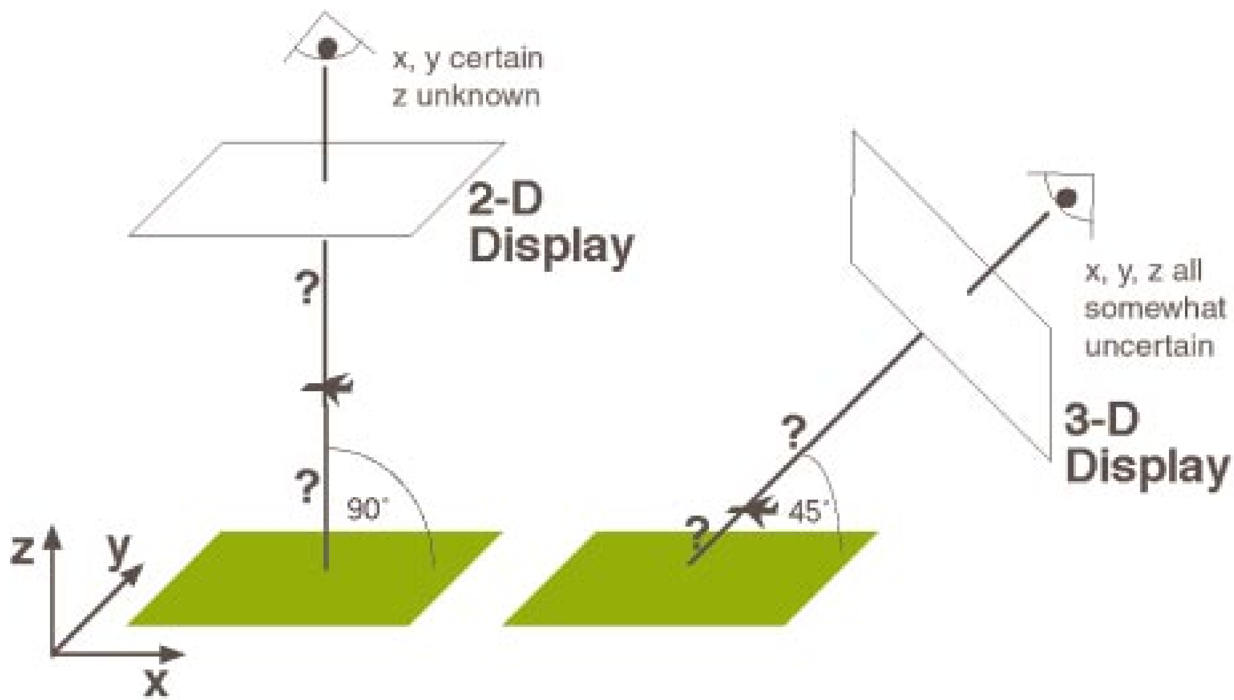

Figure 2. LOS ambiguities for 2-D and 3-D displays.

LOS ambiguity is resolved in vision through the use of depth cues (see Cutting and Vishton, 1995 for review). These cues are as follows:

- **Linear perspective.** The spatial dimensions of objects or terrain across the image scale become proportionally smaller with distance. For example, railroad tracks pinch together in the distance and appear to recede.

- **Relative size.** The relative sizes of familiar objects in the view can be used to gauge their relative distances. For example, large objects are closer than small objects.
- **Texture.** The relative densities of texture on surfaces change as the surface recedes into the distance. For example, the visual gradient of rocks and pebbles on a beach specifies its orientation and shape in depth.
- **Shading.** The surfaces of objects vary in intensity as that surface's orientation with respect to the light sources in the scene varies. For example, the gradient from light to dark across a face helps specify its shape in depth.
- **Occlusion.** Closer objects fully or partially obscure farther objects. For example, the ships and planes are in front of the terrain in figure 1 because they occlude it (rather than it occluding them).
- **Atmospheric haze.** The contrast of features in the distance is decreased because of light scattering from atmospheric haze. For example, a distance ridge appears fainter than a near one.
- **Stereo disparity.** The relative positions of objects at different depth shifts slightly in the two eyes' views, reflecting each eye's slightly different view of the world. For example, stereo viewing of a scene can yield more vivid depth than viewing the scene through either eye alone.
- **Accomodative blur.** Objects away from the plane that is being looked at (accomodated) are out of focus. For example, distant text on a cathode ray tube (CRT) blurs when one looks at one's fingers close up.
- **Convergence of the two eyes.** Looking at a near object creates a muscular strain that can be used to guage the object's depth. The cue is inneffective beyond a 10-ft viewing distance because the direction of gaze is so straight as to be indistinguishable from parallel.

In table 1, the nine depth cues are broken down by whether they are obtainable in one eye's view (monocular), by comparison between the two eyes' views (binocular), or from signals about the physical state of the eyes, such as lens shape and direction of gaze (ocular-motor). The cues are listed by their availability to vision in the real world, their availability in the AADC display shown in figure 1, and whether they are manipulated in the present study.

Of the nine cues in table 1, two are fully available and two are partially available for air track localization in the static view of the 3-D display shown in figure 1. Linear perspective and occlusion are fully available. Relative size is somewhat available. The size of the realistic symbols is scaled somewhat with distance. However, the relative scaling is not fully realistic. To facilitate recognition, planes are larger relative to ships than they are in the real world, and they do not shrink below a certain critical size in the distance. Shading is available only on the realistic symbols. The display is flat, so binocular and ocular-motor cues are not available.

Why are more cues not available? Although it is technically feasible to include them, there are trade-offs preventing all depth cues from being included in 3-D displays. Tactical displays highlight salient information. Some of the monocular cues add clutter. At some point, adding these cues will interfere with information saliency. Texture, haze, and blur are usually excluded. Other cues are not used because of expense and practicality. Stereo technologies are cumbersome and expensive. Motion displays are computationally demanding and largely unexplored. New true volumetric displays (e.g., Soltan, Lasher, Dahlke, McDonald, and Acantilado, 1998) and flat-screen real-time lenticular displays (e.g., Travis, Lang, Moore, and Dodgson., 1995) that combine stereo and motion are still in their infancy.

Table 1. Natural static depth cues and artificial augmentations available to real-world vision and to static 3-D displays for localizing an object in depth.

Natural Static Depth Cues		Available in Real World	Available in AADC (Figure 1) Display	Manipulated in This Study
Monocular	Linear Perspective	Yes	Yes	Yes
	Relative size	Yes	Somewhat	Yes
	Texture	Yes	No	
	Shading	Yes	Somewhat	
	Occlusion	Yes	Yes	
	Atmospheric haze	Yes	No	
Binocular	Stereo disparity	Yes	No	
Ocular-motor	Accomodative blur	Yes	No	
	Convergence of the two eyes	Yes	No	
Artificial	Drop-lines	No	No	Yes
augmentations	Drop-shadows	No	Yes	Yes

LOS ambiguity in 3-D displays can be reduced by increasing the number of depth cues available (e.g., Nagata, 1993). The best supported formulation of how depth cues are combined in the visual system is that each cue generates its own depth signal, and these signals are then combined to optimally estimate depth (Landy, Maloney, Johnston, and Young, 1995). Thus, more cues lead to more accurate depth estimation. Supporting this formulation, Bruno and Cutting (1988) tested depth perception for all possible combinations of four depth cues (size, occlusion, motion, and perspective) and found that cues were integrated additively and linearly with the other cues. In the present study, we expect to find improvement in localization accuracy in a perspective view display by varying the monocular cue of relative size. We scaled track symbol size so that it is consistent with linear perspective (smaller in the distance, larger up close).

An alternative approach to adding depth cues has been taken by some 3-D display designers. Cognizant of the LOS ambiguity issue, designers have added artificial augmentations to localize the position of objects in space unambiguously (for review, see Wickens, Todd, and Seidler, 1989). Two commonly employed artificial augmentations are (1) a reference line or ‘drop-line’ (also known as an altitude post) from the symbol onto the ground plane to unambiguosly specify 2-D location, or (2) a “drop-shadow”(also known as a ground truth shadow) directly under a symbol on the ground plane. For example, the AADC prototype display shown in figure 1 uses drop-shadows for all aircraft. Drop-shadows and drop-lines specify x and y on the ground plane. Altitude (z) can be estimated either from the length of the drop-line or from the distance between the track symbol and its drop-shadow. These augmentations have an associated cost. Yeh and Silverstein (1992) have labelled these augmentations “crutches” because they clutter the display with unnatural additions. For example, drop-shadows essentially doubles the number of air track symbols in the display. How well these augmentations work, how they interact with display density (clutter), and how they are combined with natural depth cues are questions that we address here.

Another issue with 3-D displays is the depiction of far distances. Because the viewpoint is tilted towards the ground plane more in a 3-D view (figure 1), far objects and terrain are allotted less display space than near objects. This display is beneficial in that it acts as a cue to depth (it is associated with the cue of linear perspective from table 1), but it is detrimental in that it reduces fidelity for distant objects. Here, we examine how the compression of the distance in 3-D displays affects the spatial localization of tracks and whether it interacts with the two artificial augmentations and with clutter.

OBJECTIVE

The objective of this study was to test potential performance benefits of adding the depth cue of track size and drop-lines and drop-shadows to 3-D displays to improve track localization. This study was conducted in support of the Space and Naval Warfare Systems Center, San Diego (SSC San Diego) program called Perspective View Technology.

METHOD

PARTICIPANTS

The participants were 20 researchers and staff recruited from SSC San Diego, 16 men and 4 women. Most participants (18 of 20) participated in our earlier study (Smallman, Schiller, and Mitchell, 1999). The participants' average age was 41 years.

MATERIALS

Materials Related to Independent Variables (What Was Manipulated)

As figure 3 shows, six different 3-D views were created, one for each combination of track size cue (constant versus changing) by augmentation condition (drop-lines, drop-shadows, or none). We also created one top-down 2-D view. The independent variable manipulations were not applicable. Track size was held constant and there were no depth cue augmentations. Thus, seven views were created.

The displays were shown to participants on the high-resolution monitor of a Silicon Graphics Indigo® workstation. The display was 9 ¼ inches high by 12 inches wide. There were 28 assorted tracks shown as realistic symbols. There were 14 air tracks and 14 surface tracks shown with a mix of different platform types and force (i.e., friendly versus hostile) affiliations (colors). The same 28 tracks were present in each view, but in different locations. Although, LOS ambiguity is mainly a concern for air tracks floating in space, we included surface tracks in our stimuli to test the track size manipulation and provide more realism.

The terrain was similar to that used in our earlier study (Smallman et al., 1999), water and land topography from the Straight of Hormuz in the Persian Gulf. There were two terrain regions designated as 'close' and two regions designated 'far.' The regions were rhomboid-shaped so that they occupied the front corners of the 3-D displays when the terrain was rendered in 3-D perspective (see figure 4). The horizontal (x, y) co-ordinates of the tracks for each display were always constrained to lie in one of these four regions. The regions to the left of the terrain were designated 'cluttered' regions because five air and five surface tracks were placed in each. On the right of the display, each larger 'uncluttered ' region only housed two air and two surface tracks. Thus, two variables were manipulated within each display (distance and track density) and two variables were manipulated between each display (track size and augmentation). We digitally altered the map so there was approximately the same amount of land and sea in each region and the land topography was of roughly comparable complexity. Specifically, we removed a series of islands that could have been used to aid track localization by the strategy of comparing subtle terrain features between the display and the test map.

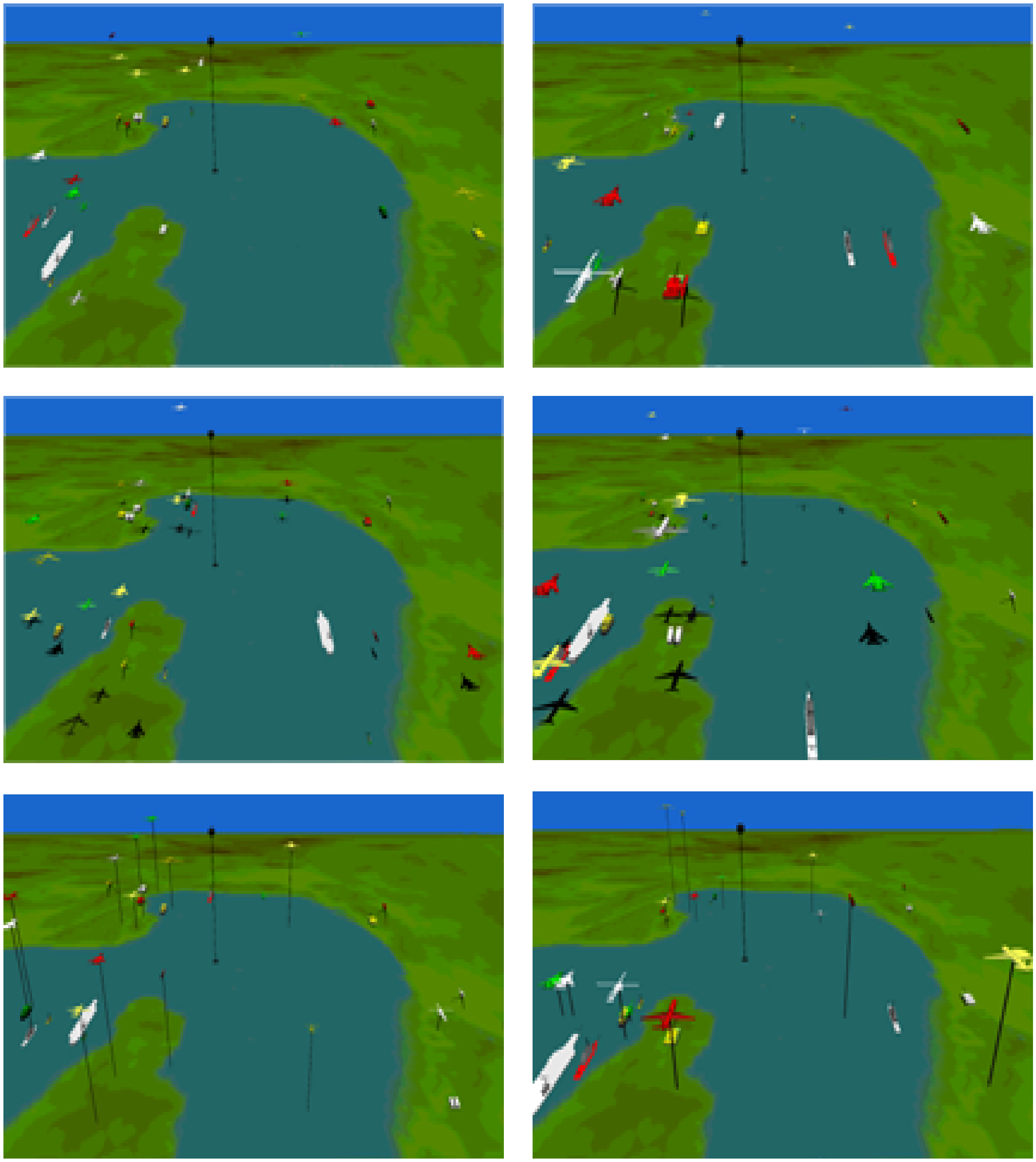

Figure 3. Six experimental 3-D views. Tracks are all the same size (left column). Tracks are smaller with distance (right column). No depth cue augmentations added to perspective view (top row). Drop-shadows added to perspective view (middle row). Drop-lines added to perspective view (bottom row).

We arranged the tracks in a pseudo-random way in the four regions such that there was minimal pictorial overlap of the tracks when the scenes were rendered in 3-D. We did this because we wanted to measure localization performance and not recognition performance. We mitigated the most deleterious effects of clutter by minimizing potential ambiguity in finding and identifying individual tracks on the display. The air tracks were assigned a random altitude between 0 and 36,000 ft. To give participants a reference for their altitude judgments, there was a 36,000-ft black reference line in each of the 3-D displays (see figure 3). We depicted all the air tracks in level flight, and all tracks headed north because we were examining localization of tracks in 3-D space, but not the specific orientation in 3-D space at a given location. The camera, shown schematically in figure 4, was tilted down at a 25-degree viewing angle to the ground plane. The field of view (FOV) of the camera was 86-degrees horizontally and 66 degrees vertically. The 2-D display was created in the same manner as the 3-D displays except that the scene was rendered from directly above.

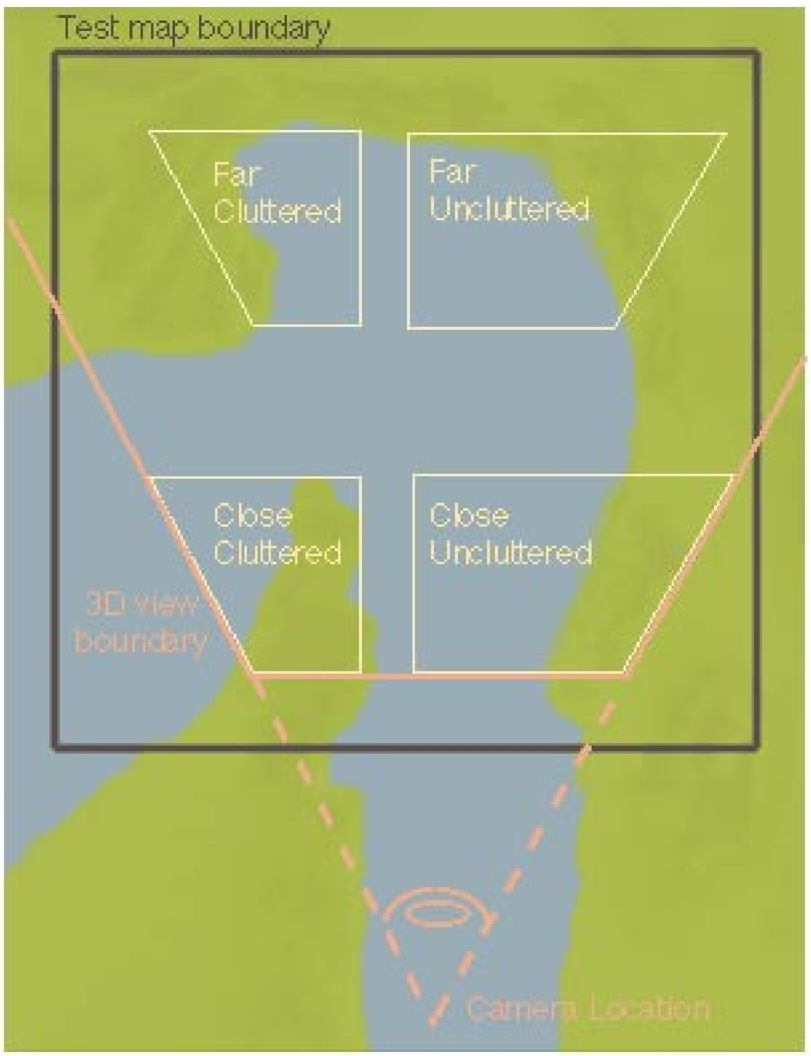

Figure 4. Plan view background topography. The color printout for the paper test sheet is outlined in black. The location of the camera for the 3-D view and its horizontal FOV is red. The four regions of track placement are yellow.

Materials Related to Dependent Variables (What Was Measured)

Participants reconstructed the scene on a test sheet. The test sheet is a large (11.5-inch square) high-resolution color printout of the background topography on matte paper, (see figure 5). Participants reconstructed track positions by placing 28 track symbol pins into perceived locations on this test map. The display and the test sheet were always visible. The pins were located above the test sheet (see figure 5). The pins had colored plastic heads. We mounted a small laminated color printout of the track symbol on each pin. We went to these lengths to minimize the chance that participants would make the wrong mappings from depicted tracks to track pins. The test sheets were mounted on a foam board and placed on an easel next to the participant. Participants constructed a new test sheet for each of the seven views.

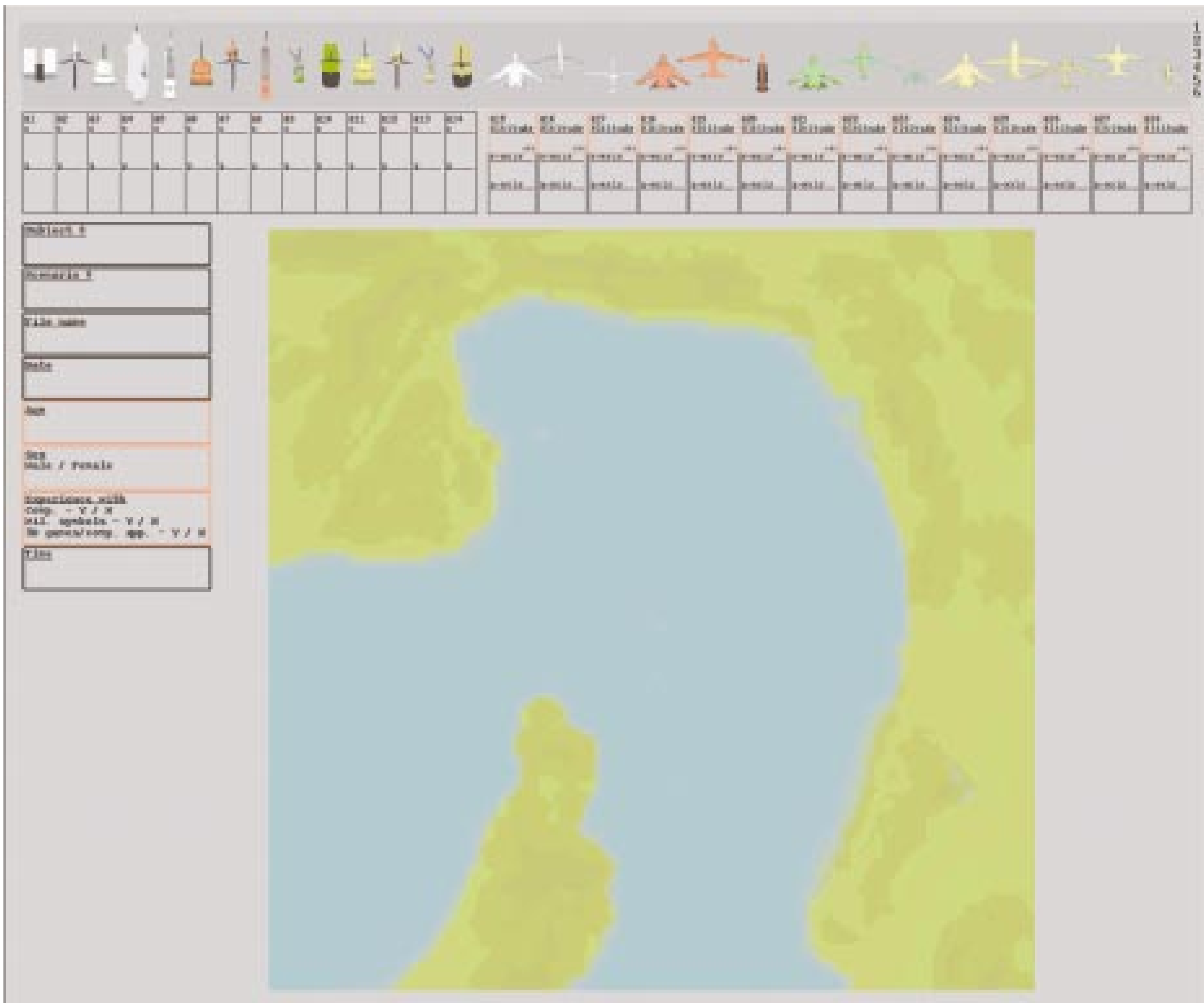

Figure 5. Test sheet.

DESIGN

Each participant filled in seven test sheets, one for each of the seven views. Table 2 describes the five independent variables tested in the design by level descriptions and reference figures.

Table 2. List and descriptions of the five independent variables.

Variable manipulated	N levels	Level descriptions	Figures showing manipulations
Track size	2	Constant versus semi-realistic scaling with distance	Left versus right column of figure 3
Artificial augmentation	3	Drop-lines versus drop-shadows versus no augmentation	Three rows of figure 3
Distance	2	Close versus distant	Near tracks versus far tracks in each view in figure 3
Track density	2	Many tracks versus few tracks	Left versus right sides in each view in figure 3
Display format	2	2-D versus 3-D	Figure 3 displays with 2-D view similar to figure 6

PROCEDURE

Phase 1

Participants were read a brief description of the study. Then they signed a consent form. The two participants that had not participated in our earlier experiment (Smallman, Schiller, and Mitchell, 1999) were tested for normal color vision (Ishihara) and acuity (Snellen). They passed both tests.

Participants sat approximately 19 inches from the computer display. An easel with test sheets mounted on foam board was to the right. The easel was illuminated from above with an incandescent light. The rest of the room was dimly illuminated. This lighting allowed for good color reproduction of the test sheet while minimizing glare on the display screen.

Participants practiced putting pins into maps. They placed five pins into a map mounted on foam board at each of five locations denoted by small black dots.

Phase 2

Participants were provided training on the map pinning task. They were shown a 2-D map of a peninsula (the practice map) containing six tracks headed north on the display (figure 6). On the easel was a paper copy of the map mounted on foam board. Pinned into the map on the foam board were six track pins in the same locations as those shown on the 2-D view. Participants were told that their task in the main experiment would be to place track pins into maps in the locations they thought they were shown on the display screen. All participants seemed to readily understand this task.

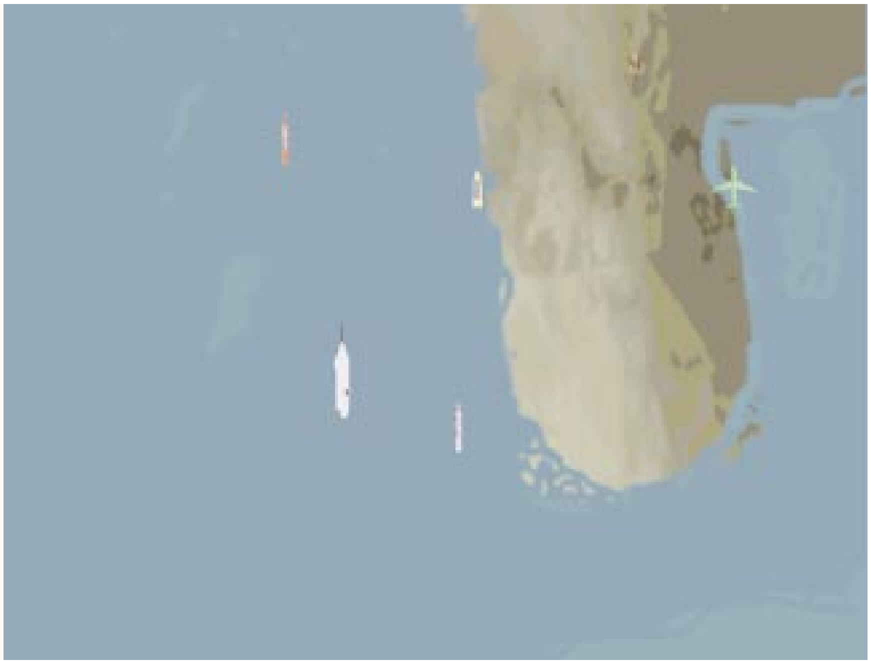

Figure 6. Training screenshot shown to participants to explain the map pinning task.

Phase 3

We then introduced participants to the 3-D manipulations being tested in the study by showing them a screenshot of a 3-D view of a peninsula (the practice map) populated with realistic tracks symbols (see figure 7). We explained to the participants that on the left-hand side of this display the track symbols changed in size so that the symbol for the cargo vessel at the bottom of the display was large when it was close and small when it was in the distance. On the right-hand side of the display, the symbols did not change size with viewing distance. On the left-hand side of the display, the location directly below air tracks on the ground plane was denoted by a drop-shadow, while on the right-hand side, it was shown by a drop-line. We explained that the drop-line in the center of the display connecting a small black sphere with its drop-shadow was an altitude reference. Its altitude was always 36,000 ft and was present in each 3-D view. We told the participants that they would have to gauge the altitude of air tracks shown to them in the 3-D displays and that they should make their judgments using this reference. We pointed out that all of the six aircraft in figure 7 were at the same altitude as the reference. We gave participants 5 minutes to study the screenshot to familiarize themselves with the coding scheme.

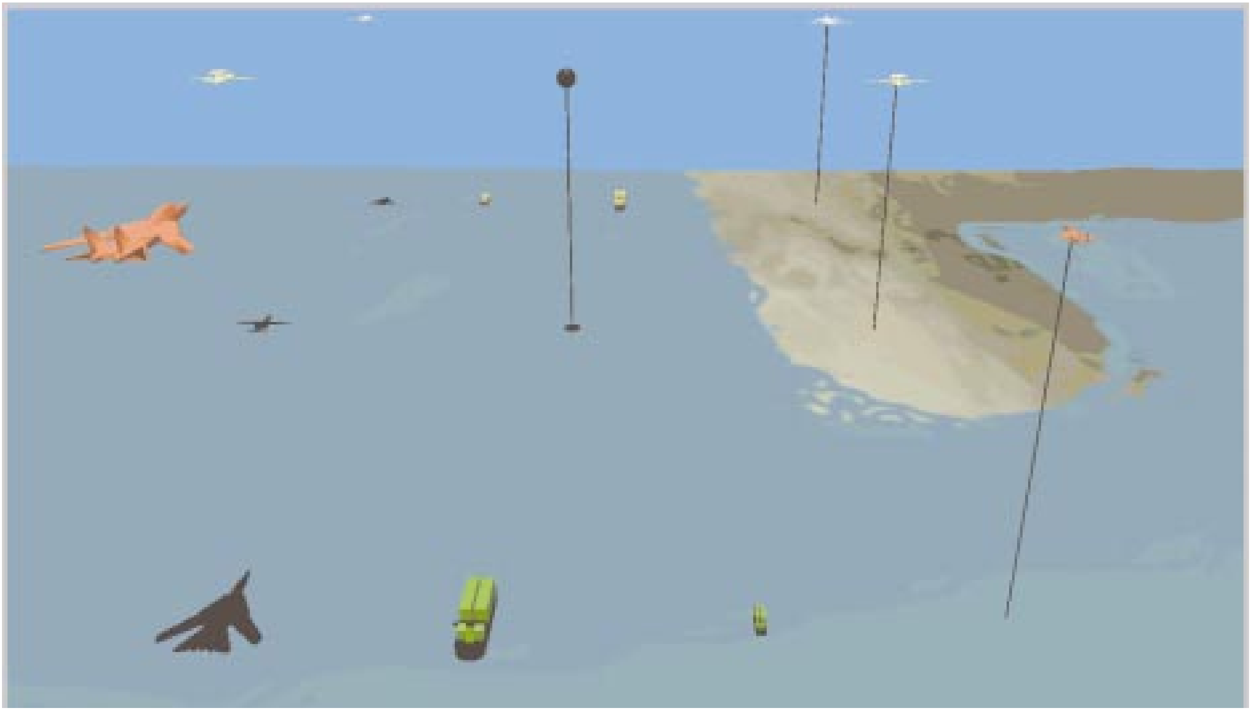

Figure 7. Training screenshot shown to participants to explain the 3-D artificial augmentations and track size depth cue manipulations in the study.

Phase 4

In the main experimental phase of the experiment, participants viewed the seven displays and completed test sheets for each as accurately as possible. The six 3-D views were presented first in random order. We did not want to 'tip-off' participants that the track locations had been constrained to lie in the four regions described earlier, so we always ran the 2-D condition last. Participants pinned the 28 track symbols on the test sheet as shown on the display screen. Next, for each 3-D view, participants wrote their estimates of perceived altitude for the 14 air tracks to the nearest 1,000 ft in the red response boxes on the test sheets (see figure 5). Altitude was not provided on the 2-D view, so this stage was skipped for the 2-D display condition. The time it took participants to fill in each test sheet was recorded. To minimize fatigue and to keep participants on track to finish all data entry in about 1.5 hours, we prompted them at 10 and 15 minutes into a trial to finish.

The participants were debriefed after completing all seven test sheets. The experimenters scored the test sheets. First, pins were removed and the track number, 1 through 28, was written next to each pinhole. Second, a fine Cartesian grid printed on a heavy transparent plastic overlay was superimposed on the map and carefully aligned with it. The coordinates for each track were recorded to the nearest thousand of feet. The coordinate system was defined as x (horizontal across the display), y (depth 'into' the display) and z (altitude). We calculated the x, y, and z misalignments for all of the tracks. Misalignment refers to the distance between the true and estimated 3-D locations of a track. Small misalignments imply good accuracy (good localization performance) and large misalignments imply poor accuracy (poor localization performance).

RESULTS

GROUND PLANE (X,Y) MISALIGNMENT

Misalignment on the ground plane represented the distance in thousands of feet between the estimated ground point (in x,y) from the test sheet and the true ground point for each track. Ground plane misalignment was calculated for each track for each participant and was averaged across conditions. Figure 8 shows mean misalignment for air tracks for the size and artificial augmentation conditions.

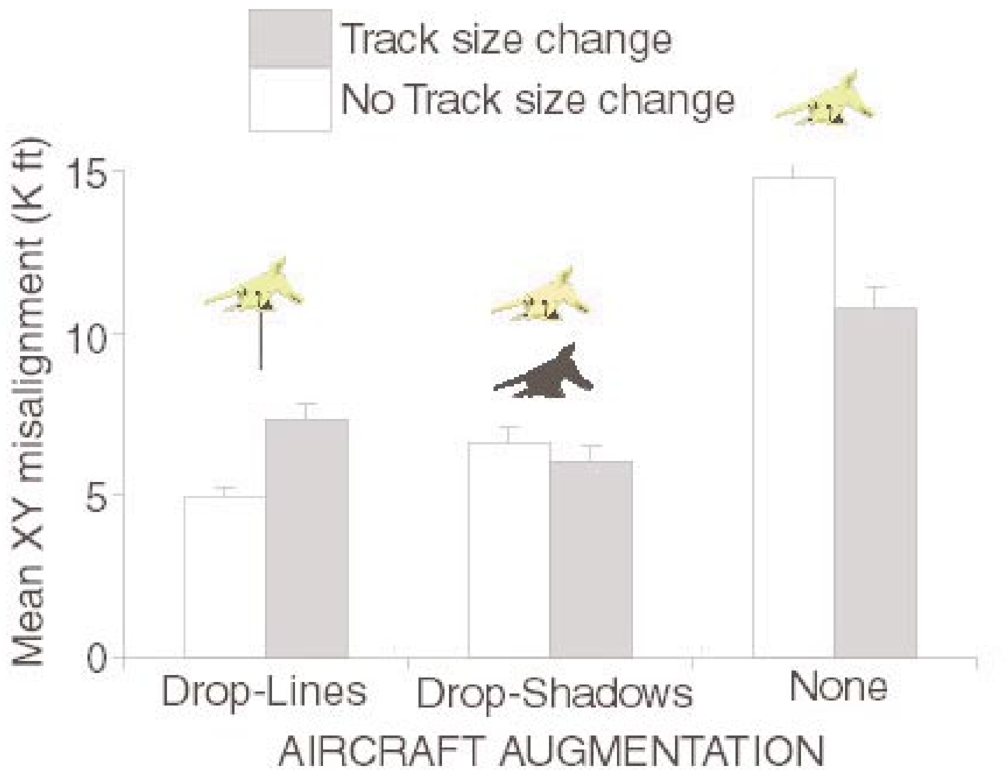

Figure 8. Mean misalignments in the ground plane by augmentation and track size condition. Example of air track symbology is shown above the augmentation conditions.

Artificial Augmentations

The addition of artificial augmentations to the air tracks ($F(2,18) = 57.6$, $p < 0.0001$) dramtically improved localization performance. The average misalignment without artificial augmentations to help localize aircraft over the ground plane was 12,774 ft compared to 6,225 ft when a drop-line or a drop-shadow was present. Post-hoc pair-wise comparisons among the different conditions shown in figure 8 revealed that the best localization performance was for constant size air tracks with drop-lines[1] ($t(18) = 4.0$, $p < 0.05$).

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[1] All post-hoc tests were Bonferroni *t* tests. In this case, it was significantly better than the nearest performer.

Track Size

Varying track size did not improve localization accuracy overall for the air tracks. However, there was a significant interaction between track size and the different artificial augmentations ($F(2,38) = 18.0$, $p < 0.0001$). Relative size improved performance when it was the only depth cue available. Size improved localization performance by 27% (misalignment dropped from 14,765 ft to 10,721 ft). However, changing the size of tracks with artificial augmentations did not increase performance. Performance was actually better for aircraft with drop-lines and no size change than when size change was the only depth cue available ($t(18) = 5.0$, $p < 0.001$). Thus, the naturalistic size depth cue and the artificial augmentation depth cues of drop-lines and drop-shadows did not combine to improve performance. In addition, the average misalignment for the ships (which was 7,975 ft) was not improved by varying the size of the track symbols.

Display Format, 2-D versus 3-D Performance

Performance on the top-down 2-D view was compared with performance on the 3-D displays. Figure 9 shows performance for localizing surface and air tracks in 2-D and 3-D. Note that 3-D augmentations apply to air tracks only. Because track size did not change in the 2-D view, the data summarized for 3-D are only from the unchanging track size conditions. Also, it should be noted that misalignment was measured in the ground plane only (x and y), because altitude was not estimated in the 2-D condition.

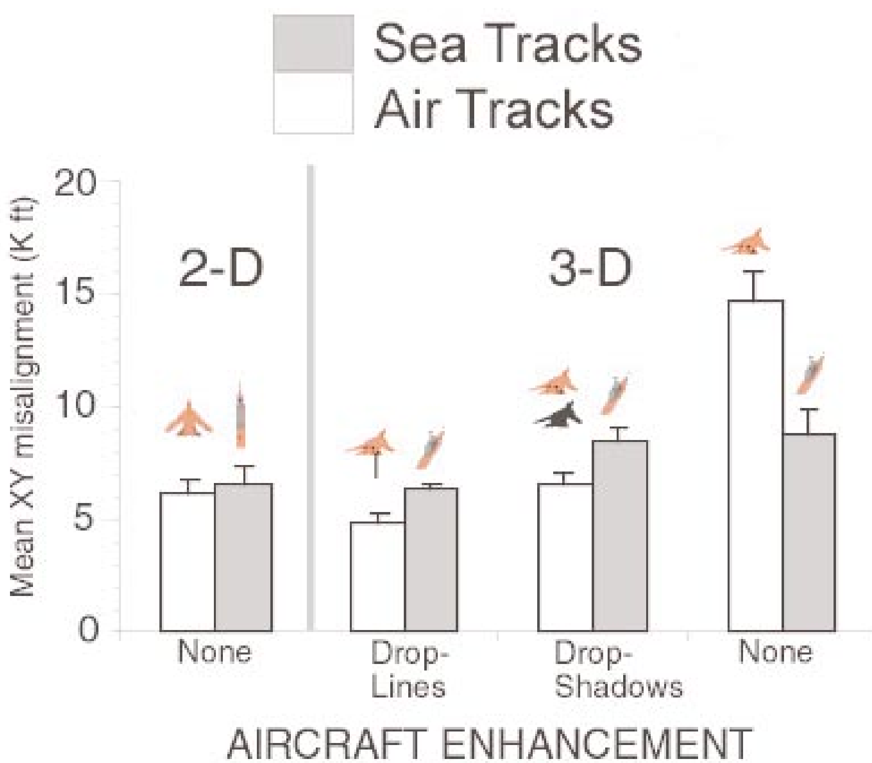

Figure 9. Localization performance for 2-D versus 3-D for sea tracks and air tracks by augmentation condition.

We found that ground localization performance with 2-D top-down view was only better than 3-D views when there was no 3-D augmentations present ($F(1,19) = 21.6$, $p < 0.0001$). However, we found a marginally significant interaction between display and platform category for the drop-line augmentation ($F(1,19) = 4.0$, $p < 0.06$). Participants appear to localize aircraft slightly better in 3-D than in 2-D if drop-lines were available.

Distance and Density

Unanticipated subtleties in participant strategies and unexpected sensitivities to 3-D rendering camera geometry made the distance and display manipulations hard to interpret. Foreshortening reduced the fidelity of the distant regions such that the near regions were five and a half times larger (in terms of screen area) in 3-D perspective view than the far regions, although they were both of equal size on the ground plane (see figure 3). However, there was an overall significant effect of distance with distant air tracks localized *better* than near tracks ($F(1,19) = 30.0$, $p < 0.0001$). Rather than unexpectedly good localization performance in the distant regions, we suspect this reflects unexpectedly poor performance in the near regions. Observation of several participants engaged in the pinning task in near regions revealed a surprising strategy. Tracks near the bottom of the displays were sometimes localized at the bottom of the test map in the ‘gutter’ region between the bottom of the close region and the edge of the test map (see figure 3). The same behavior was not exhibited at the top of the test map where the sea was clearly demarcated from the terrain. This strategy led to more inaccuracy in the near regions. In addition, participants mentioned that they had noticed that the drop-lines of air tracks were not vertical and track symbols were not vertically aligned with their drop-shadows, when they were near the edges of the display. Figure 4 shows the drop-lines “splaying out,” particularly near the edges of the screen. This splaying is an inevitable consequence of perspective projection resulting from barrel distortion (Ray, 1988). It is more commonly known as “fishbowling.” Because this distortion increases with distance from the center of the 3-D display, it distorts the near regions more than the far regions because the near regions are closer to the edge of the display (see figures 3 and 4). This extra distortion in the near regions compared to the far regions may have contributed to the poor near performance and to the unexpected distance effect.

An unexpected lesson learned from conducting this study was how critical camera geometry may be when rendering a scene in perspective. As mentioned above, the relatively large FOV we used led to barrel distortion (fishbowling). This complicated interpretation of the distance manipulation. Barrel distortion is roughly proportional to the reciprocal of the cosine of the FOV (Ray, 1988), and thus it increases with FOV. Others have informally noted that fishbowling becomes perceptually salient for FOVs greater than 60 degrees (e.g., Fleck, 1994). McGreevy and Ellis (1986) asked participants to make judgments of direction between two points in a 3-D air traffic control display as FOV was manipulated from 30 to 120 degrees in 30-degree increments. They found significant distortions for the 90- and 120-degree conditions. Presumably, this distortion was from barrel distortion. Barrel distortion has the effect of shifting the images of objects far away from the vanishing point even further away. In our displays, it shifted high altitude aircraft in the close regions towards the edge of the screen (see the center and right columns of figure 4 for examples of the drop-lines tilting and fanning out like flowers). This shift could have made the localization task harder. There is a design trade-off with FOV. Large FOVs promote better Situation Awareness (SA). Yet, large FOVs lead to distorted displays. The optimal FOV for 3-D tactical displays remains to be determined.

The density manipulation was also hard to interpret. There was an overall significant effect for density that was in the opposite direction from that predicted. Overall, air tracks were localized more accurately in high-density regions ($F(1,19) = 23.5$, $p < 0.0001$). We have no ready explanation for this result. It could be caused by either of two factors. First, as mentioned above, we minimized track occlusions so that participants could locate and identify tracks in the displays. Minimizing track occlusions might have minimized the critically deleterious aspect of high-density regions. Second, localization in high-density regions may be easier because tracks act as landmarks for each other and help performance.

ALTITUDE (Z) MISALIGNMENT

In addition to misalignment in the ground plane, we assessed misalignment of altitude (z) for air tracks. Figure 10 shows the mean misalignments for aircraft altitude estimates by the size change and augmentation conditions. This breakdown is the same as that shown in figure 8 for ground localization performance.

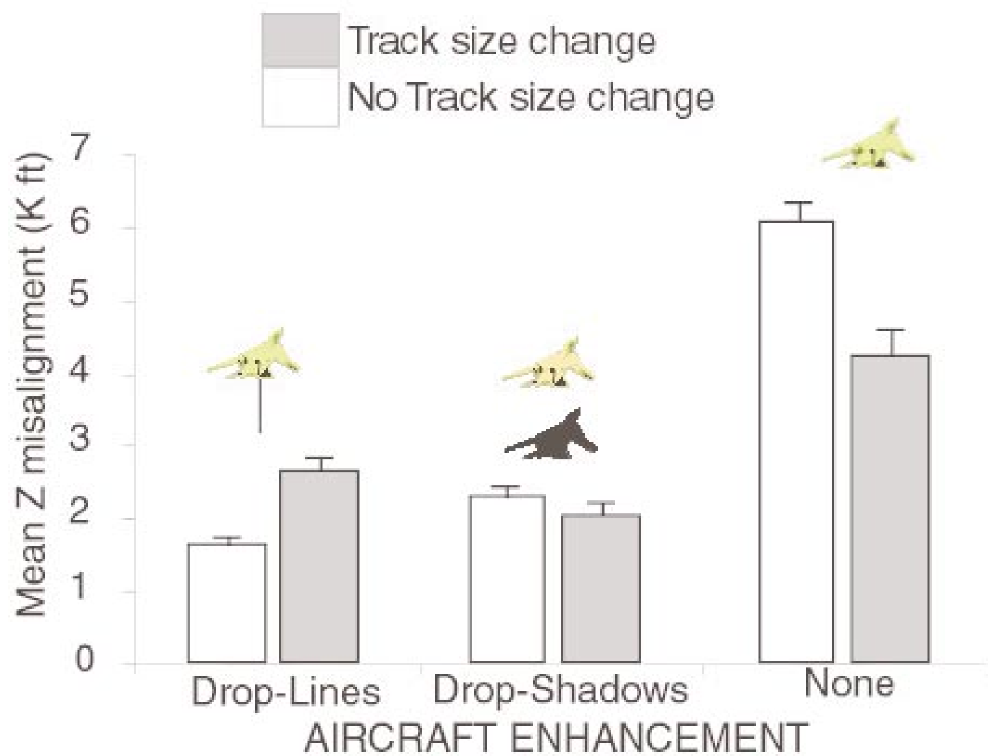

Figure 10. Mean altitude (z) misalignments plane by augmentation and track size condition. Example of air track symbology is shown above the augmentation conditions.

Altitude (z) accuracy was improved by the addition of artificial augmentations to the air tracks ($F\ (2,38) = 85.0$, $p < 0.0001$). Average z misalignment varied about fourfold from 6,000 ft for no augmentation without size cues down to 1,633 ft with drop-lines without size cues. For comparison, 1,633 ft is about 4.5% of the length of the altitude reference (see figure 7). There was an overall improvement in accuracy for varying track size ($F\ (1,19) = 7.2$, $p < 0.05$) except for drop-lines or drop shadows augmentations ($F\ (2,38) = 46.2$, $p < 0.0001$). Post-hoc comparisons revealed that aircraft with drop-lines but no size change were localized significantly better than any other size/augmentation combination[2] ($t\ (18) = 4.3$, $p < 0.05$).

[2] See footnote 1.

GENERAL DISCUSSION

3-D perspective views without size depth cues or augmented depth cues are poor for localizing tracks. Adding either a drop-line or a drop-shadow to an air track symbol improved localization performance by 100%. Adding the depth cue of relative track size led to a modest (27%) improvement in localization performance. However, contrary to indications from previous research, when there were drop-lines or drop-shadows present, the track size depth cue conferred no additional benefit. Natural depth cues add and combine in a weighted sum (Bruno and Cutting, 1988; Landy et al., 1995). We found that natural (size) and artificial depth cues (our augmentations) may combine nonlinearly. It is as if the size cue is not a factor when an augmentation is present. Thus, reducing the size of realistic track symbols with increasing distance is inadvisable for good localization unless no other depth cues are used. Also, reducing the size of realistic track symbols may be inadvisable for recognition.

Of the two artificial augmentations examined here, participants localized the best with drop-lines. Drop-lines were effective because they unambiguously specified the location of the aircraft on the ground plane to within the width of the drop-line. A perspective view has the unexpected benefit of separating the air track symbol from its 2-D location on the ground-plane. With drop-lines, track location is seen more accurately than the larger drop-shadows or symbols on the ground plane. Supporting this contention is the fact that the difference between ground plane localization for the 3-D view with drop-lines and the top-down 2-D view is half the average size of a symbol. In fact, performance with 3-D views with drop-shadows improves (although only slightly) when the shadows are smaller.

The superiority of drop-lines with no track size change extended to altitude judgments as well. Judging the length of a line proved more accurate than judging the distance between a track symbol and its associated shadow. Drop-lines have two further advantages over drop-shadows. First, they lend themselves more readily to further augmentation. We could improve altitude accuracy with small tick marks on a drop-line for 5,000- or 1,000-ft intervals. The empty space between a shadow and its associated symbol cannot be so demarcated. Small ticks on drop-lines may be an unobtrusive method of depicting a grid in the z dimension for a track's altitude. However, if what military decision-makers simply require is a rough categorical altitude estimate for air tracks (e.g., low, medium, or high) then unadorned drop-lines and drop-shadows may suffice. Second, in a cluttered display, drop-shadows impose unnecessary workload by forcing users to maintain perceptual "links" between each symbol and its drop-shadow. Drop-lines might be preferable because they connect symbols to the ground plane in an uninterrupted way. This uninterrupted way may not require as much mental "bookkeeping." Performance with drop-shadows was slightly better when the track size changed with distance. Tracks are more easily linked to the ground plane if their drop-shadows can be differentiated in size from other drop-shadows.

SUMMARY

We tested the potential performance benefits of adding depth cues and other augmentations to 3-D displays to improve track localization. Participants viewed tracks in augmented 3-D displays or in a 2-D top-down display, and then reconstructed the track positions on blank paper maps with track symbol pins. We found the following:

- Drop-lines and drop-shadows significantly improved the localization of aircraft over no augmentations for 3-D displays.

- Augmenting 3-D displays with drop-lines and drop-shadows improved ground-plane localization performance to the level of 2-D displays.
- Drop-lines led to the best overall localization performance for 3-D displays.
- Varying the size of track symbols with distance for 3-D displays improved localization only when there were no drop-lines or drop-shadows present.

RECOMMENDATIONS

Based on the results of this experiment, we recommend the following:

- Air tracks should be augmented with drop-lines in 3-D perspective view displays.
- Track symbols on 2-D top-down displays should be augmented with a salient dot to indicate precise ground location.
- Tic marks on drop-lines should be investigated to improve accuracy of altitude judgments.

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